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A fundamental residue pitch perception bias for tone language speakers

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A FUNDAMENTAL RESIDUE PITCH PERCEPTION BIAS FOR TONE LANGUAGE SPEAKERS

by

ELIZABETH PETITTI

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Approved by

First Reader

Tyler Perrachione, Ph.D.
Assistant Professor of Speech, Language, and Hearing Sciences

Second Reader

Melanie L. Matthies, Ph.D.
Senior Associate Dean
Associate Professor and Chair of Speech, Language, and Hearing Sciences

Third Reader

Gerald D. Kidd Jr., Ph.D.
Professor of Speech, Language, and Hearing Sciences

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ABSTRACT

A complex tone composed of only higher-order harmonics typically elicits a pitch percept equivalent to the tone's missing fundamental frequency (f_0). When judging the direction of residue pitch change between two such tones, however, listeners may have completely opposite perceptual experiences depending on whether they are biased to perceive changes based on the overall spectrum or the missing f_0 (harmonic spacing). Individual differences in residue pitch change judgments are reliable and have been associated with musical experience and functional neuroanatomy. Tone languages put greater pitch processing demands on their speakers than non-tone languages, and we investigated whether these lifelong differences in linguistic pitch processing affect listeners' bias for residue pitch. We asked native tone language speakers and native English speakers to perform a pitch judgment task for two tones with missing fundamental frequencies. Given tone pairs with ambiguous pitch changes, listeners were asked to judge the direction of pitch change, where the direction of their response indicated whether they attended to the overall spectrum (exhibiting a spectral bias) or the missing f_0 (exhibiting a fundamental bias). We found that tone language speakers are significantly more likely to perceive pitch changes based on the missing f_0 than English speakers. These results suggest that tone-language speakers' privileged experience with linguistic pitch fundamentally tunes their basic auditory processing.

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INTRODUCTION

Pitch perception is a complex phenomenon. Speakers use pitch to signal linguistic and pragmatic information, including stress, emotion, and interrogatory intent (Moore, 2008; Beach, 1991). In languages where tone creates lexical distinctions, pitch is essential to lexical semantics (Fromkin, 1978). The perceptual phenomenon that allows listeners to hear such a wide and rich spectrum of information is much more complex then a simple relationship between frequencies (Plack, Oxenham, & Fay, 2006). The frequency of the waveform, physical and neurological responses of the listener, and differing environmental conditions all affect pitch perception. Although fundamental frequency may be the acoustic correlate of pitch, the perceptual realization of this pitch is entirely subjective (Moore, 2008).

Pitch perception abilities vary widely across individuals. Twin studies demonstrate genetic variation responsible for differing musical pitch perception abilities among listeners (Drayna, Manichaikul, de Lange, Sneider, & Spector, 2001). Underlying cortical differences also contribute to difficulties with pitch perception in amusia, where tone-deaf individuals have difficulty with both musical and linguistic pitch (Tillman *et al.,* 2011).

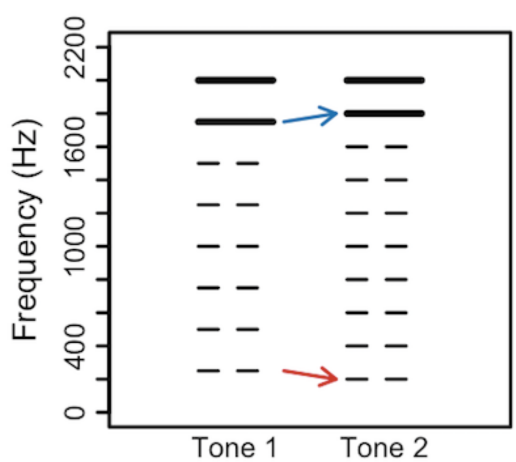
The range of individual pitch perception abilities may be partially attributed to differences in training or perceptual experiences. Musical training has been shown to improve f_0 perception (Schön, Magne, & Besson, 2004) and change the way musicians analyze pitch (Wong, Skoe, Russo, Dees, & Kraus, 2007). Linguistic experience also affects the way pitch is perceived, with tone language speakers displaying language-specific perceptual strategies for both speech (Stagray, Downs, & Sommers, 1992) and nonspeech signals (Bent, Bradlow, & Wright, 2006).

One impressive demonstration of individual differences in pitch perception stems from judgments about how pitch changes in pairs of complex tones composed of only higher-order harmonics and missing energy at their f_0. Usually, a complex tone composed of only higher-order harmonics elicits a pitch percept equivalent to the tone's missing f_0 in a phenomenon known as “virtual,” “missing fundamental,” or “residue” pitch (e.g., Licklider, 1951; Schouten, 1940). Residue pitch is a common phenomenon regardless of the presence or absence of f_0, and often accompanies pitch perception of complex tones (Moore, 2008). However, when asked to judge the direction of the pitch change between two tones with a missing f_0, listeners can give individually consistent yet diametrically opposite answers (Smoorenburg, 1970) – some may hear the pitch change as “going up,” whereas others may hear the same change as “going down.” While certain acoustic factors reliably affect listeners' residue pitch change judgments (e.g., Plomp, 1967), consistent individual bias persists (Schneider *et al*., 2005; Ladd *et al*., 2013).

1.1. The residue pitch task

Individual differences in residue pitch perception were originally explored by Smoorenburg (1970) in an attempt to further define the acoustic parameters of residue pitch. The stimuli set contained two tones with two higher order harmonics and missing low fundamental frequencies. The tones were played in succession, and listeners were required to judge the direction of pitch change. Although all participants heard the same tone pair, the experimental design revealed inhomogeneous answers among different participants. Listeners heard the pitch move either up or down depending on which harmonic information they attended to: the implied f_0 (the spacing between the present harmonics) or the overall spectral height (the averaged frequencies of the individual components). The tones illustrated in **Figure 1** depict this phenomenon. Listeners who perceive a residue pitch change based on the spacing between harmonics (i.e., the missing f_0) will respond that the change in the tones' pitch moves downward. Conversely, listeners who perceive the residue pitch change based on the global shift in frequencies of the present partials will respond that the change in the tones' pitch moves upwards.

Figure 1. Smoorenburg's original residue pitch judgment task. Both tones are comprised of two present harmonics (solid lines) with the same top frequency (2000Hz). The number of missing harmonics (dotted lines) dictates the f_0 for Tone 1 (250Hz) and Tone 2 (200Hz). If listeners perceive the pitch as moving "up" (blue arrow), they demonstrate a spectral bias based on the change in frequencies of the present harmonics; "downward" moving pitch percepts (red arrow) demonstrate fundamental bias based on the change in implicit f_0 (harmonic spacing).



1.2. Residue pitch in general pitch processing theories

Two general theories of pitch perception – place and temporal – suggest different physiological explanations for the residue pitch phenomenon. Helmholtz's place theory involves a spectral profile derived from the vibrations in the auditory signal (as cited in Moore, 2008). Different frequencies excite different regions of the tonotopically-organized basilar membrane so that the listener derives pitch from the pattern of maximal excitation (f_0). With this theory, residue pitch perception is not the physical equivalent of f_0 perception, where both register the same excitation on the basilar membrane; rather, residue pitch arises from analysis of the pattern of harmonic excitation that is similar to that of f_0 (Schouten, 1940). Determining the spacing between partials in a tone generates a pitch that corresponds to the missing f_0. As the spacing between these partials decreases, so does their resolvability and stimulation of residue pitch. Higher order tones with less resolvable harmonics still generate residue pitch percepts at an above-chance level; however, this ability decreases with increasing harmonic order and raises the possibility of different processing mechanisms for tones with resolvable and unresolvable harmonics (Houstma & Smurzynski, 1990; Norman-Haignere, Kanwisher, & McDermott, 2013).

Place theory is further explained by Terhardt (1974), who suggested the inclusion of a learning phase. In this phase, the auditory system compares detected frequencies to a pre-learned formula in order to synthesize the residue pitch. These formulas, or harmonic templates, are formed during cochlear filtering of sound, where auditory inputs are then compared to all probable responses in order to generate the corresponding harmonic template (Shamma and Klein, 2000). In this way, the final output (perceived f_0) is uniform regardless of the harmonic makeup of its input signal. Tones with residue pitch may still generate a pitch percept in line with the implied f_0 due to the activation of a stored harmonic template.

In contrast, the temporal theory of pitch perception suggests that auditory perception is related to the firing pattern of evoked neural impulses instead of locations on the basilar membrane (Schouten, 1940). Residue pitch in this model is determined by analysis of the time window between the aggregated partials' waveform, or the periodicity of the total waveform (Schouten, 1940; Licklider, 1951). Pitch perception through this model is dependent on the most salient time interval, in accordance with either its loudness or in comparison to previous sounds (Moore, 2008). Residue pitch perception arises through an analysis of the time window between peaks of the waveform; multiple possible time intervals may result in certain auditory ambiguities. These ambiguities can account for listeners with different perceptual bias for residue pitch tone pairs, and may suggest potential influence from hemispheric preference for temporal signals (Schouten *et al.,* 1962; Poeppel, 2003).

Evidence against temporal theories, however, stems from studies that still find residue pitch perception in tones presented dichotically (one harmonic to each ear) (Houtsma & Goldstein, 1972) and for tones where the frequency components are presented in different phases (Renken, Wiersinga-Post, Tomaskovic, & Duifhuis, 2004). These findings contradict Schouten's theory, which predicts that phase modulation of different frequency components would impact residue pitch perception. Instead, these results indicate that residue pitch perception occurs at a central level once auditory information from both channels is combined, relying on a more *gestalt* pattern recognition process (Terhardt, 1974).

1.3. Acoustic influence in residue pitch processing

Certain acoustic factors reliably affect residue pitch perception. Early psychoacoustic work demonstrated the importance of periodicity in perceived pitch, where the absolute frequency contributes more to the perception of a tone than the physical f_0 (Plomp, 1967). In complex tones, harmonics below the sixth order can dominate pitch perception and contribute more to f_0 resolution of tones missing energy at f_0 than those with a harmonic order of H7 or above (Ritsma, 1967; Houtsma & Fleuren, 1991; Moore, Glasberg, & Peters, 1985). Other studies suggest a higher threshold for the cutoff for less resolvable harmonics, occurring near the 10^{th} partial (Houtsma & Smurzymaki, 1990; Bernstein & Oxenham, 2003). Additionally, this threshold may increase for some participants by changing the phase relationship of the partials (Renken *et al*., 2004), or presenting dichotic tones (Bernstein & Oxenham, 2003), allowing listeners to resolve partials up to the 20^{th}. Despite this variation, harmonic resolvability generally decreases as harmonic number increases from H5-H8, even across changes in the spectral or absolute frequency (Moore & Gockel, 2011).

Pitch salience also increases as the number of harmonics present in the tone increases (Plomp, 1967) and, correspondingly, a larger number of present harmonics leads to more fundamentally biased percepts (Schneider *et al.,* 2005; Ladd *et al*., 2013).

The perceptual impact of these acoustic variations are consistent among listeners, such that more f_0-based pitch percepts are seen with lower-order, more resolvable, tones with increasing number of present harmonics (Schneider *et al.,* 2005; Ladd *et al*., 2013).

1.4. Individual variation in residue pitch processing

Studies have shown consistent neuroanatomical and perceptual variation in residue pitch processing. Individuals with fundamentally biased percepts also display increased gray matter in left Heschl's gyrus and greater left-lateralized auditory evoked potentials (Schneider *et al.,* 2005). A larger left Heschl's gyrus is also correlated with the ability to successfully learn linguistic pitch patterns (Wong *et al.,* 2008). Neural differences are also seen for musicians, where improved brainstem encodings of pitch are related to enhanced linguistic pitch perception abilities (Krishnan, Xu, Gandour, & Cariani, 2005; Wong *et al.,* 2007; Bidelman, Gandour, & Krishnan, 2010).

Pitch perception abilities are improved for musicians for both melodic pitch (Schön, *et al.,* 2004) and linguistic pitch (Wong *et al.,* 2007). Greater incidence of absolute pitch is seen with earlier start ages for musical training (Deutsch, Henthorn, Marvin, & Hu, 2005). Musicians not only respond more accurately to small pitch changes in a foreign language than do nonmusicians (Marques, Moreno, Castro, & Besson, 2007), but they are also able to detect weak f_0 manipulations better than nonmusicians (Schön, *et al.,* 2004). This increased pitch sensitivity carries over to speech-related mechanisms; musical experience in speakers of a non-tonal language enhances their ability to use lexical pitch information to learn novel lexical items (Wong, Perrachione, & Parrish, 2007). Although the relationship between musical training and pitch perception might suggest that musical experience should impact residue pitch perception, the results so far have not been consistent. Some studies have found greater fundamental bias in musicians (Seither-Preisler *et al*., 2007), whereas others have not found this effect (Schneider *et al.,* 2005; Ladd *et al.,* 2013).

Listeners' long-term linguistic environment has also been shown to affect the neuroanatomical and perceptual biases of pitch. Tone language speakers demonstrate increased gray and white matter in the right anterior temporal lobe and left insula medial to Heschl's gyrus (Crinion *et al.,* 2009). Traditional right-hemisphere lateralization of pitch processing seen in English listeners (Zatorre, Evans, Meyer, & Gjedde, 1992) is different from linguistic processing of pitch by tone language speakers, which recruits key left hemisphere structures: PET studies show that Mandarin speakers have additional activation of left hemispheric sites when detecting linguistic pitch (Klein, Zatorre, Milner, & Zhao, 2001; Hsieh, Gandour, Wong, & Hutchins, 2001), and Thai speakers have increased activation in left-hemisphere Broca's area for phonologically significant pitch variations (Gandour *et al.,* 2000).

Functionally, tone language speakers demonstrate more accurate pitch recognition for stimuli with linguistic pitch under degraded listening conditions (Stagray *et al.,* 1992) and better categorical perception of lexical tones (Liu, 2013) when compared to speakers of a non-tone language. Perceptual differences based on linguistic background are also seen for non-speech stimuli (Bent *et al.,* 2006), where improved musical pitch perception and production (Pfordresher & Brown, 2009) and greater sensitivity to f_0 amplitude modulation (Kreiman & Gerratt, 2010) are seen for speakers of a tone language compared to non-tone language speakers. The extent, however, to which native language-based differences may also affect residue pitch perception is not yet known.

1.5. The experiment

Tone language speakers privilege pitch information in a different way than English speakers, demonstrating both behavioral and functional neuroanatomical differences in pitch perception. Although research has shown that tone languages emphasize pitch during language acquisition (Fromkin, 1978), it is so far unknown whether these lifelong differences in pitch processing affects basic auditory biases. Taking into account the cortical and brainstem differences in pitch perception, listener bias for residue pitch tasks may be, in part, explained through the way listeners are predisposed to extract, analyze, and encode pitch information (Hsieh *et al.,* 2001; Bent *et al.,* 2006). Given the increased demands of pitch perception for speakers of tone languages, we hypothesized that tone language speakers will be more sensitive to the consistent harmonic relationships associated with a specific f_0 (e.g., Shamma & Klein, 2000), and will therefore have a greater fundamental bias when judging residue pitch change in pairs of missing-f_0 tones. In this study, we asked native speakers of English and native speakers of tone languages to make residue pitch change judgments for pairs of missing-f_0 complex tones. Our results indicate that tone-language listeners privilege implied-f_0 information significantly more than English listeners when attending to this basic, non-linguistic auditory processing task.

METHODS

2.1. Subjects

Two groups of participants completed this experiment: native tone language speakers and native English speakers. The tone language group (*N* = 40, 10 male and 30 female, age 18-28, *M* = 21.4 years) was comprised of native speakers of Mandarin (*N* = 21), Cantonese (*N* = 5), bilingual Mandarin/Cantonese (*N* = 11), and Vietnamese (*N* = 3). The English language group (*N* = 40, 9 male and 31 female, age 18-26, *M* = 20.4 years) had no prior exposure to a tone language. All participants demonstrated normal hearing by passing a basic audiometric screening (see Procedure, below) and had a self-reported history free from speech, language, or hearing difficulties. Information about participants' musical history was collected through self-report and displayed in **Table 1**.

All included participants demonstrated accurate judgments of ambiguous pitch change (e.g., Semal & Demany, 2006) with > 90% performance on a control task (see below); 31 additional participants were recruited but not included because their pitch judgments were not reliable (< 90% control task accuracy).

Table 1. Musical experience of English-speaking and tone-language speaking participants.

	Language			
Musicality	English		Tone Language	
	M	*SD*	*M*	*SD*
Start age (years)	8.66	2.80	7.82	3.92
Number years played	5.98	4.66	7.78	5.62

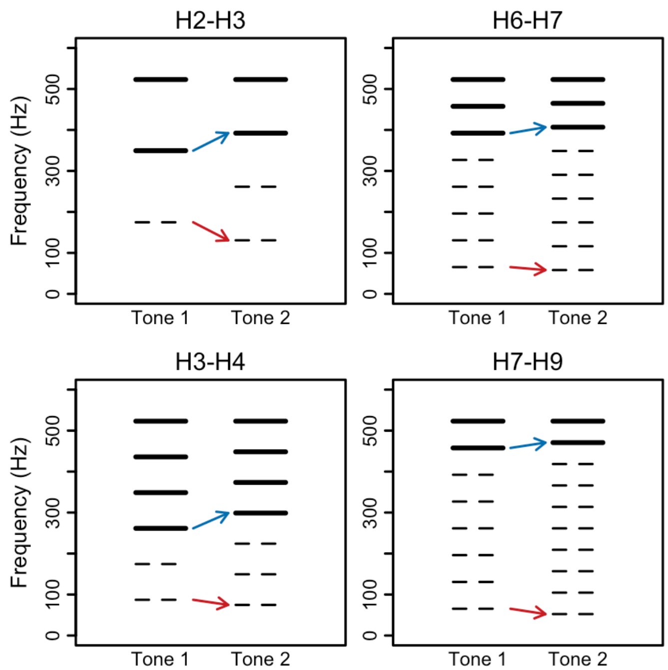
2.1. Stimuli

All stimuli were synthesized in Praat with a sampling rate of 44.1 kHz at 16 bits. Each tone was presented for 500ms at 50dB SPL in order to prevent combination tones (e.g., Plomp, 1967), with 10ms linear rise-fall times, and a 250ms silent interval between tones in a pair.

2.2.1. Experimental stimuli

Initially, we synthesized 72 pairs of harmonic complex tones with missing-f_0 components. Following Schneider *et al.* (2005), we assessed residue pitch change judgments across a range of acoustic factors by parametrically varying the number of present harmonics, the frequency of the highest present harmonic, and the order of harmonics. Examples of these manipulations are depicted in **Figure 2**. The number of present harmonics (2, 3, or 4) and the frequency of the highest-order harmonic (293, 523, 932, 1661, 2960, or 5274Hz) were kept constant across the two tones in a pair. This allowed the difference in implicit f_0 to be determined by the harmonic order (Ladd *et al*., 2013). The harmonic order between the two tones differed such that the lowest present harmonic changed (from H2-H3, H3-H4, H6-H7, or H7-H9) while the frequency of the highest component was kept constant to reduce the presence of edge pitch (Kohlrausch, Houtsma, & Evans, 1992; Schneider *et al.,* 2005). These manipulations resulted in tones with implicit f_0 of 24-1758Hz, present frequency components of 146-5274Hz, and mean spectra of 212-4977Hz. A breakdown of the parameterization of experimental tones is included in **Appendix A**.

Figure 2. Stimulus parameterization for residue pitch change judgment task. Four example stimulus pairs are shown, titled with the shift in lowest present harmonic. In the top left panel, Tone 1 is composed of two present harmonics (solid lines) at 349 and 523Hz with an implicit f_0 of 174Hz; Tone 2 is also composed of two harmonics, now at 392 and 523Hz, and with an implicit f_0 of 131Hz. Red arrow: residue pitch change percepts based on missing f_0 (fundamental listeners). Blue arrow: residue pitch change percepts based on the upward shift in frequencies of the present partials (spectral listeners).



2.2.2. Control tones

It has previously been noted that there are some listeners who, despite being able to hear a pitch difference between two tones, are unable to make reliable perceptual decisions about the direction of pitch change for unambiguous tonal stimuli (Semal & Demany, 2006). In order to ensure that participants in our study were making accurate, authentic judgments about their perceptual experiences of pitch change, we included control tones with an unambiguous pitch difference that matched the spectral composition and implicit f_0 of experimental tones. Control stimuli consisted of 12 pure tones (f_0 = 195-4102Hz) and 12 complex tones in which both f_0 and all higher-order harmonics were present (f_0 = 37-1055Hz, H1-H12 present). Pure tone pairs were matched to the lowest spectral energy seen in the experimental set. Complex tone pairs were chosen to match differences in f_0 within tone pairs for each of the six top harmonics seen in the experimental set (Δf_0 = 5.23-138.42Hz), and parameterized to match the range of harmonic orders seen in the experimental set (H1-H12). A full breakdown of control tones is included in **Appendix B**.

2.1. Procedure

Participants were seated in a sound-attenuated chamber. Stimuli were delivered over Sennheiser HD380 Pro circumaural headphones via a Behringer FCA1616 USB audio interface, controlled by PsychoPy (v1.80.0). Participants first completed a basic audiometric screening in each ear consisting of octave-spaced pure tones from 1000-4000Hz at 20dB HL. Participants were familiarized with the experimental task by completing 24 practice trials consisting of complex and pure tone pairs with unambiguous pitch changes. Participants received automatic feedback on the accuracy of their pitch judgments during the practice trials. None of the practice tones were included in the experiment.

The pitch-change judgment task was based on previous experimental designs examining missing-f_0 tones (e.g., Schneider *et al.*, 2005). Instructions were presented verbally for each participant (see **Appendix C** for instruction script). The task trials were broken into two runs of 72 trials each, separated by a self-paced break. All tone pairs were presented in both rising-f_0 and falling-f_0 orders, counterbalanced across the two runs, so that there was no design bias in the direction of implicit f_0 change. Participants responded via keyboard, pressing the "up" arrow for perceived rising pitch and the "down" arrow for perceived falling pitch. The experiment was self-paced, and lasted approximately 30 minutes.

2.1. Data analysis

Listeners' response to each trial was assigned a value of "0" to indicate a spectral pitch judgment (i.e., rising harmonic frequencies → rising pitch percept) or a value of "1" to indicate a fundamental pitch judgment (i.e., more closely spaced harmonics → falling pitch percept). Overall listener bias (i.e., the probability of a fundamental pitch judgment, $P(f_0)$) was calculated by computing the average of pitch judgment scores across all experimental trials, yielding a number between 0 (completely spectral bias) and 1 (completely fundamental bias). Trials with response times exceeding two standard deviations from a participant's mean were excluded from analysis.

Inferential statistics on participant responses were conducted using generalized linear mixed effects models for binomial data with fixed factors including Group (English vs. tone language) number of present harmonics (2, 3, or 4), and harmonic order (low vs. high). A maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013) was used in the design of this model, including within-participant intercepts and slopes and within-stimulus intercepts.

2.1. Stimulus confounds

During the original synthesis of these stimuli, a rounding error occurred that caused 36 complex tones to be synthesized without the intended highest harmonic, affecting the harmonic relationship between 36 tone pairs. As a result, 72 trials were excluded from the analysis, and the results below are based on *only* the 72 trials where tone pairs with correct harmonic composition were presented to listeners. Included in the analyzed data are 13 pairs with two present harmonics, 11 with three, and 12 with four. A full breakdown of the experimental tone pairs included in the experiment is depicted in **Appendix B**.

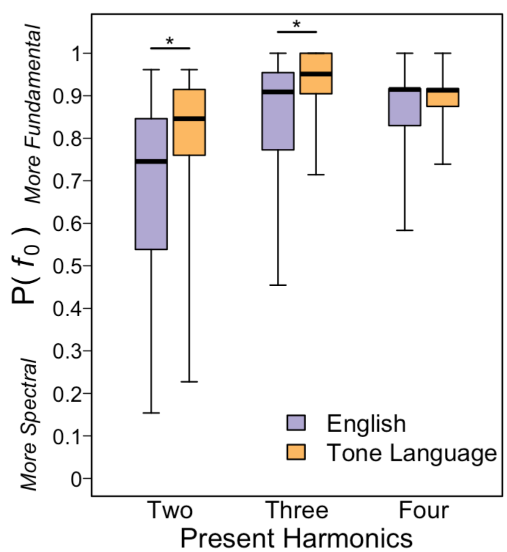
3. RESULTS

3.1. Linguistic factors affecting P(f_0)

Aggregating over all experimental trials, individual English listeners' P(f_0) ranged from 0.39-0.96 (M = 0.80), while individual tone-language listeners' P(f_0) ranged from 0.61-0.96 (M = 0.88). Unlike previous studies (Schneider *et al*., 2005; Ladd *et al*., 2013), no participants exhibited completely spectral (P(f_0) = 0) or completely fundamental (P(f_0) = 1) perceptual biases. Tone-language speakers displayed significantly greater P(f_0) perceptual bias than native English speakers ($z = 3.25$, $p = 0.00116$). Interestingly, this difference was retained across stimuli containing two present harmonics ($z = 3.53$, $p = 0.0004$, Cohen's $d = 0.78$) and three present harmonics ($z = 3.16$, $p = 0.00158$, $d = 0.66$), but not four present harmonics ($z = 0.99$, $p = 0.32$, $d = 0.21$). These differences are depicted in **Figure 3**.

English listeners' P(f_0) for two-harmonic stimuli ranged from 0.15-0.96 (M = 0.68), from 0.45-1.00 (M = 0.85) for three-harmonic, and from 0.58-1.00 (M = 0.87) for four-harmonic. Tone-language listeners' P(f_0) ranged from 0.23-0.96 (M = 0.81) for two, from 0.71-1.00 (M = 0.93) for three, and from 0.74-1.00 (M = 0.89) for four present harmonics.

Figure 3: P(f_0) is significantly higher for tone speakers with tones with two and three present harmonics, but not four. As more harmonic information is added to stimuli, both English and tone language listeners display increasing P(f_0).



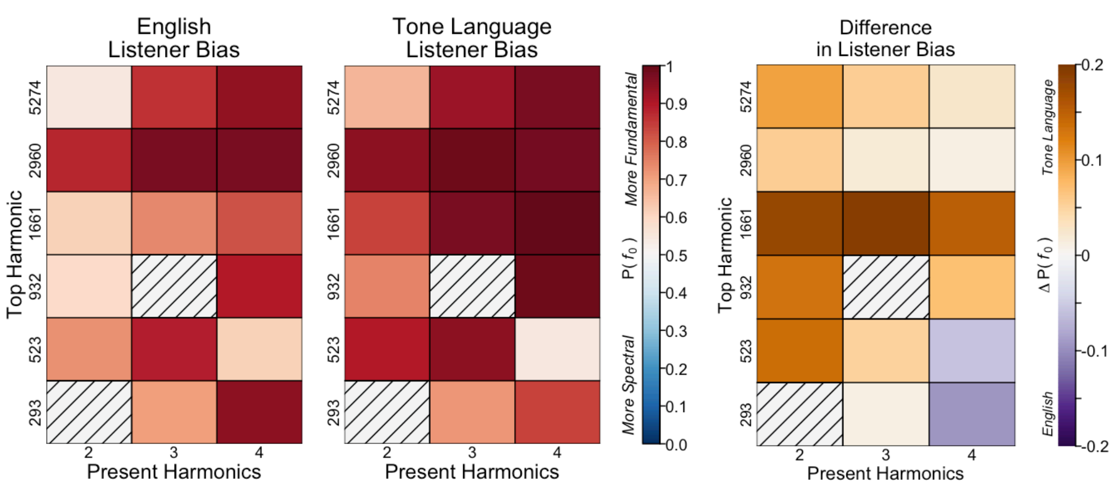
3.2. Acoustic factors affecting P(f_0)

Consistent with previous studies (Schneider *et al*., 2007; Seither-Preisler *et al*., 2007; Ladd *et al*., 2013), both listener groups demonstrated increasing P(f_0) as the number of harmonics increased: pitch-change responses for three-harmonic stimuli were significantly more fundamental than for two-harmonic stimuli (z = 2.72, p = 0.00654);

however, P(f_0) did not differ between three- and four-harmonic stimuli (z = 0.24, p = 0.81). The trend for increasing P(f_0) with increasing acoustic information was consistent across both groups (no language × harmonic composition interaction; z = 0.41, p = 0.68).

There was no significant increase in P(f_0) across groups with an increase in mean spectrum (z = 1.354, p = 0.18), and no group × spectrum interaction (z = 0.41, p = 0.68). These relationships are depicted in **Figure 4**. However, given previous studies demonstrating the reliability of increased P(f_0) with increased spectral height (Schneider *et al.,* 2005; Ladd *et al.,* 2013), it may be the case that these results may have achieved significance with a fuller set of stimuli targeting the spectral heights in this experiment.

Figure 4: P(f_0) for tone-language and English speakers as a function of number of present harmonics and frequency space (left). Greater P(f_0) values (dark red) are found for higher spectral components and increasing number of harmonics. Differences between language groups (ΔP(f_0), right) reveal systematically greater f_0 residue pitch perception in tone language speakers relative to English speakers. It is important to note two null cells (top harmonic of 293Hz with two present harmonics; top harmonic of 923Hz with three present harmonics) due to no included stimuli with these features.

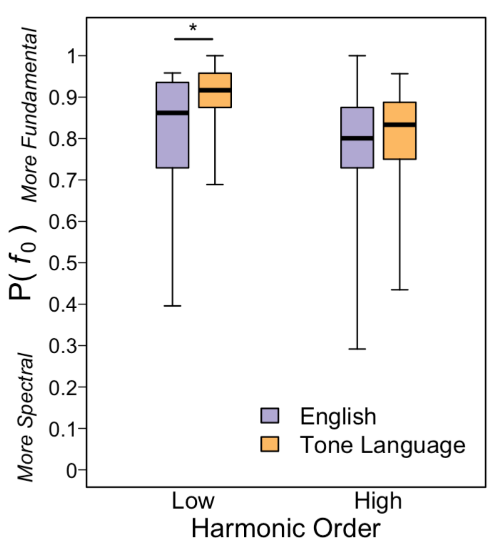


3.3. Resolvability

Group differences were examined for low harmonic order (lowest present harmonic < H6, $N = 24$) and high harmonic order (lowest present harmonic > H6, $N = 12$) (i.e., Ritsma, 1967; Houtsma & Fleuren, 1991). Overall, there was no significant group difference for harmonic order collapsed across languages ($z = 1.08$, $p = 0.28$). There was, however, a significant group interaction (language x harmonic order) ($z = 2.97$, $p = 0.00301$).

For tones with low, resolvable spectra, tone language speakers' P(f_0) ($M = 0.91$) was significantly higher than English speakers' P(f_0) ($M = 0.81$) ($z = 4.104$, $p = 4.06\times10^{5}$). This group difference was not observed for tones with higher-order harmonics ($z = 1.034$, $p = 0.30$). These differences are depicted in **Figure 5**.

Figure 5: P(f_0) is significantly higher for tone speakers with tones with low order, resolvable harmonics (lowest present harmonic < H6). Both English and tone language listeners display more spectral bias for tones with high order, less resolvable harmonics. There is a group interaction effect (language × harmonic order) present, suggesting increased P(f_0) response with greater harmonic resolvability for tone language speakers (e.g., Shamma & Klein, 2000).



3.4. Musical factors affecting P(f_0)

Given research demonstrating effects of musical training on pitch perception (Wong *et al.,* 2007; Schön *et al.,* 2004) and previous reports of residue pitch perception differences between musicians and nonmusicians (Seither-Preisler *et al*., 2007), we examined the impact of musical training on P(f_0). To avoid a confounding effect of language background, and for our results to be comparable with those of Seither-Preisler and colleagues (2007), we analyzed the effect of musical background for only native English-speaking participants. We found no evidence that number of years played (r = -0.012, p = 0.94) nor start age (r = 0.058, p = 0.73) affected P(f_0), corroborating other studies that also found no effect of musical training on residue pitch perception bias (Schneider *et al.,* 2005; Ladd *et al.,* 2013).

3.5. Consistent responses

Individuals' responses to tones with residue pitch are subjective, and verifying the validity of responses on a trial-by-trial basis is difficult. However, because we presented each tone pair twice (once in rising-f_0 and falling-f_0 order), we can examine how consistent listeners' subjective judgments of pitch change were across tone pairs by repeating our inferential statistics on only this set of stimuli (i.e., same P(f_0) response for identical tone pairs in the two different conditions).

Listeners made relatively consistent judgments in tone pairs across the two experimental runs (M = 86%, SD = 6%). Consistency measures did not differ between tone language speakers (M = 85%, SD = 3.5%) and English speakers (M = 84%, SD = 3.6%) (z = -0.25, p = 0.81). This result differs from the results reported by Ladd *et al.,*

(2013) who found certain subjects susceptible to an order of presentation effect.

After eliminating inconsistent responses, a significant group difference in P(f_0) between tone language and English speakers (z = 2.6, p = 0.0097) was retained. Significant group difference was also retained across two harmonic stimuli (z = 3.048, p = 0.0023, d = 0.61) and three harmonic stimuli (z = 2.36, p = 0.018, d = 0.56). Additionally, effects of harmonic resolvability were still seen, with group differences remaining significant for lower order harmonics (z = 3.38, p = 0.00072) but not higher order harmonics (z = 0.46, p = 0.64).

Two changes in statistical significance were noted when excluding inconsistent responses: the interaction effect between language and harmonic order was lost (z = 1.58; p = 0.11) (although the pairwise differences remained), and a significant increase in P(f_0) across groups with an increase in mean spectrum was seen (z = 2.67; p = 0.0075), whereas this was not present in the original analysis.

4. DISCUSSION

4.1. Linguistic factors and group differences

We investigated individual differences and acoustic factors in residue pitch perception between native speakers of English and of tone languages. Native speakers of tone languages exhibited a consistent and significantly greater bias to perceive residue pitch changes between pairs of complex tones based on the change in implicit f_0 (harmonic spacing) than native English speakers. This language-based difference was consistent across a variety of acoustic factors that independently affected P(f_0) and demonstrated a reliably strong effect size.

A greater bias to perceive residue pitch changes based on the implicit f_0 may be the result of lifelong increased pitch processing demands imposed on speakers of a tone language, for whom subtle pitch differences signal critical semantic distinctions between words. Improved residue pitch perception for tone language speakers supports previous findings of both speech and nonspeech pitch perception dependent on linguistic experience (e.g., Liu, 2013), where shared processing mechanisms (Bent *et al.,* 2006) may attribute language-dependent perceptual strategies to basic psychoacoustic processes.

This privileged processing of pitch in tone languages may develop during Terhardt's (1974) proposed learning phase and facilitate the association between the co-occurrence of harmonic partials and f_0 (Shamma & Klein, 2000). The formation of these harmonic templates relies on cochlear responses and filter matching such that even when f_0 is absent, the harmonic partials alone are sufficient to evoke an implicit f_0-based percept of pitch. For low order harmonics with resolvable partials, tone language speakers' stronger residue pitch perception may be attributable to these more robust harmonic templates. This is especially likely given the interaction we found between harmonic order and language.

Our finding that stronger implicit f_0-based percepts for tone language speakers for low but not higher order harmonics may lend further support to linguistic influence during auditory development, and suggest distinct processing mechanisms that mature during development and depend on resolvability (Houtsma & Smurzynski, 1990). There has been evidence suggesting that infants are born with an innate sense of pitch, where English-speaking infants were able to perceive the implicit f_0 in tones with low harmonic order (Clarkson & Rogers, 1995). This innate ability may be subjective to change based on linguistic input during early developmental years. In a study examining sensitivity in harmonic amplitudes, Mandarin speakers were shown to exhibit greater sensitivity to small differences in the amplitude of H1 (f_0) and H2 than native English speakers (Kreiman & Gerratt, 2010). Tone-language speakers' exposure to and experience with tonal contrasts may affect basic pitch processing abilities.

An alternative, and admittedly much more speculative, hypothesis for the linguistic difference in listener bias may be one that implicates the role of population genetics in linguistic differentiation, where population differences in the frequency of certain alleles correlate with typological language differences and may also influence population-level differences in basic auditory processing. There is a difference in the frequency of certain alleles of genes associated with brain growth and development between speakers of languages with and without linguistic tone (Dediu & Ladd, 2007), suggesting a relationship between genetic diversity and pressure on language acquisition and change. Tone language speakers may be genetically predisposed to acquire language and pitch processing differently from speakers of a non-tone language. Examining perceptual biases across groups with similar population-level genetics, but non-tonal languages (such as Korean and Japanese) would further delineate the extent to which the auditory system is influenced by these environmental, linguistic, and genetic factors.

Stronger fundamental bias for tone language speakers may also correlate with findings that demonstrate better capacity to imitate vocal pitch for listeners biased to perceive the missing f_0 (Postma-Nilsonová & Postma, 2013). Auditory and visual speech input increase speech production-related motor potentials in the left hemisphere, such that speech perception primes speech motor production (Watkins, Strafella, & Paus, 2003). Tone languages may create a stronger link between auditory perception and speech production (e.g., Pfordresher & Brown, 2009), and improve the linguistic representations of motor patterns stored in the left hemisphere. Previously determined neuroanatomical differences for tone and non-tone language speakers support this theory, where greater Heschl's gyrus volume in the left hemisphere is associated with both better linguistic pitch learning (Wong *et al*., 2008) and stronger fundamental pitch perception bias (Schneider *et al*., 2005). It would be interesting for future research to explore these neuroanatomical differences in both fundamentally and spectrally biased tonal language speakers to determine the extent of neuroanatomical differences.

4.2. Acoustic factors and group differences

We also examined the impact of certain acoustic factors on pitch perception independent and in relation to group differences. Reliable acoustic influence on listener bias reveals consistent perceptual responses regardless of individual variation in listener bias. Stronger fundamental bias across listeners is consistent with research demonstrating stronger responses to resolvable harmonics in comparison to unresolvable harmonics (Norman-Haignere *et al.,* 2013). A significant interaction between language and harmonic order suggests that listeners demonstrate more fundamental bias depending on linguistic experience and harmonic resolvability. Further studies may be interested in exploring these perceptual differences across a wider parameterization of harmonic information, including a more detailed look at the ambiguous two-harmonic region originally identified in Smoorenberg (1970).

We corroborated previous studies that showed fundamental pitch bias increases with increasing number of harmonics, and demonstrated that more ambiguity is seen with two-harmonic stimuli (Smoorenburg, 1970; Ladd *et al.,* 2013; Schneider *et al*., 2005). Listeners were overall consistent in their responses, and eliminating inconsistent responses did not systematically change aggregate measures of residue pitch perception bias. We did not observe the bimodal, U-shaped distribution of listener response biases reported by Schneider *et al.* (2005) despite replicating their stimuli. This may be due to the author's elimination of so-called "octave-controlled" percepts, or our limited experimental set. Instead we discovered an overall fundamental bias, in line with Ladd *et al*. (2013), Seither-Preisler *et al*. (2007), and Postma-Nilsonová and Postma (2013); however, participants in our study demonstrated less inconsistency in their pitch judgments, a matter which we address below.

It is possible that our inclusion of a rigorous set of control tones eliminated listeners who performed inconsistently on the residue pitch perception task. Participants unable to judge unambiguous complex and pure tone pitch changes (e.g., Semal & Demany, 2006) may correspondingly not be able to make reliable judgments as to their perception of change direction for residue pitches. Removing the subset of participants who responded ambiguously may change the distribution of listener bias in favor of more overall fundamental responses.

4.3. Impact of musical experience

We found no evidence that listener bias for tones with residue pitch is affected by musical expertise, suggesting linguistic experience affects basic auditory processing in a way that other individual factors do not. This impact may be related to differences in age of acquisition for language and music, where the "pitch templates" are acquired much earlier in life for tone language speakers than the later auditory learning that occurs when musical training begins in earnest. In fact, the prevalence of absolute pitch has been shown to be substantially larger for Mandarin speakers than English speakers, regardless of age of musical onset (Deutsch *et al.,* 2006). Another hypothesis is that linguistic influence on auditory perception may also be related to underlying neural differences in tone language speakers, where linguistic pitch processing recruits left hemisphere structures (e.g., Crinion *et al.,* 2009). This finding is especially interesting when considered with evidence of increased left-hemisphere gray matter for listeners with stronger fundamental bias in residue pitch perception (Schneider *et al.,* 2005).

4.4. Clinical implications and conclusion

These data suggest that lifelong experience with processing linguistic pitch in a tone language results in an auditory system that is fundamentally tuned to different features of non-linguistic, basic acoustic stimuli compared to speakers of a non-tone language. Language-based perceptual strategies influence basic psychoacoustic processing in a way that other pitch-related experiences, such as musical training, does not. This divergence may highlight the importance of pitch processing demands during early auditory development and suggest the formative role of harmonic templates. Linguistic exposure and language ability should be taken into careful consideration when working with culturally and linguistically diverse populations, particularly when considering auditory perceptual demands. Finally, these results further emphasize the importance of considering the linguistic demands of audition when developing models of basic auditory processing.

APPENDIX A

Table 2. Stimulus parameterization for experimental tone pairs, and average English speakers' and tone-language speakers' P(f_0).

Tone Pair	**Present Harmonics**	**Top Harmonic**	**Tone 1 Mean Spectrum**	**Tone 2 Mean Spectrum**	**Δ f_0**	**Average English P(f_0)**	**Average Tone P(f_0)**
6	2	523	457.63	470.70	26.15	0.73	0.89
9	2	932	776.67	815.50	77.67	0.65	0.88
11	2	932	865.43	873.75	16.64	0.49	0.65
12	2	932	873.75	885.40	23.3	0.61	0.71
13	2	1661	1384.17	1453.38	138.42	0.53	0.79
14	2	1661	1453.38	1494.90	83.05	0.69	0.88
17	2	2960	2466.67	2590.00	246.67	0.72	0.91
18	2	2960	2590.00	2664.00	148	0.95	0.97
19	2	2960	2748.57	2775.00	52.86	0.92	0.94
20	2	2960	2775.00	2812.00	74	0.92	0.97
21	2	5274	4395.00	4614.75	439.5	0.35	0.44
22	2	5274	4614.75	4746.60	263.7	0.53	0.76
23	2	5274	4897.29	4944.38	94.18	0.74	0.80
26	3	293	234.40	244.17	9.77	0.70	0.72
29	3	523	392.25	418.40	26.15	0.89	0.95
37	3	1661	1245.75	1328.80	83.05	0.71	0.96
38	3	1661	1328.80	1384.17	55.37	0.75	0.97
41	3	2960	2220.00	2368.00	148	0.94	1.00
42	3	2960	2368.00	2466.67	98.67	0.99	0.99
43	3	2960	2590.00	2631.11	41.11	0.98	0.97
45	3	5274	3955.50	4219.20	263.7	0.92	0.94
46	3	5274	4219.20	4395.00	175.8	0.91	0.97
47	3	5274	4614.75	4688.00	73.25	0.79	0.91
48	3	5274	4688.00	4794.55	106.55	0.81	0.87
49	4	293	205.10	219.75	9.77	0.95	0.83
53	4	523	366.10	392.25	17.43	0.97	1.00
56	4	523	444.55	457.63	8.72	0.26	0.08
57	4	932	652.40	699.00	31.07	0.91	0.99
58	4	932	699.00	732.29	22.19	0.87	0.97
61	4	1661	1162.70	1245.75	55.37	0.81	1.00
65	4	2960	2072.00	2220.00	98.67	0.96	1.00
67	4	2960	2466.67	2516.00	32.89	0.96	0.95
69	4	5274	3691.80	3955.50	175.8	0.97	1.00
70	4	5274	3955.50	4143.86	125.57	0.96	0.99
71	4	5274	4395.00	4482.90	58.6	0.84	0.88
72	4	5274	4482.90	4614.75	87.9	0.96	0.99

Table 3. Number of included tone pairs is indicated for each permutation of top harmonic and number of present harmonics (as seen in **Fig. 5**). Initial stimulus set contained four tone pairs per cell. Cells with 0 tone pairs correspond to null cells (diagonal lines) in **Fig. 5**.

Top Harmonic	**Present Harmonics**		
	2	**3**	**4**
5274	3	4	4
2960	4	3	2
1661	2	2	1
932	3	0	2
523	1	1	2
293	0	1	1

APPENDIX B

Table 4. Stimulus parameterization for control tone pairs and average listener response accuracy (%). Complex tone pairs were chosen to match differences in f_0 within tone pairs for each of the six top harmonics seen in the experimental set (Δf_0 = 5.23-138.42 Hz). Pure tone pairs were matched to the lowest spectral energy seen in the experimental set (f_0 = 209.20-4102 Hz).

Tone Pair	Tone Type	Tone 1 f_0	Tone 2 f_0	Δf_0	Harmonics Included	Average Listener Accuracy (%)
73	Complex	73.25	97.67	24.42	1-4	99.38
74	Complex	41.86	36.63	5.23	1-8	80
75	Complex	87.17	104.6	17.43	1-6	99.38
76	Complex	74.71	65.38	9.34	1-8	96.25
77	Complex	186.4	155.33	31.07	1-6	97.5
78	Complex	93.2	103.56	10.36	1-10	99.38
79	Complex	415.25	553.67	138.42	1-4	100
80	Complex	166.1	138.42	27.68	1-12	100
81	Complex	370	422.86	52.86	1-8	99.38
82	Complex	296	269.09	26.91	1-12	98.75
83	Complex	879	879	175.80	1-6	100
84	Complex	586	527.4	58.60	1-10	98.125
85	Pure	195.33	219.75	24.42	-	100
86	Pure	621.33	699.00	77.67	-	100
87	Pure	1453.38	1423.71	29.67	-	100
88	Pure	239.73	227.89	11.84	-	50.96
89	Pure	392.25	406.78	14.53	-	100
90	Pure	762.55	724.89	37.66	-	100
91	Pure	1480.00	1776.00	296	-	100
92	Pure	4102.00	3955.50	146.5	-	100
93	Pure	209.20	261.50	52.3	-	100
94	Pure	949.14	830.50	118.64	-	100
95	Pure	1973.33	2072.00	98.67	-	100
96	Pure	3691.80	3516.00	175.8	-	100

APPENDIX C

Experimental Protocol

________ Sign consent, language background, and supplemental forms.

________ Hearing screening

	1K	2K	4K
R:	____ ____	____ ____	____ ____
L:	____ ____	____ ____	____ ____

________ *Read instruction #1 & run practice trials*

- If participant gets more than 2-3 wrong, run practice trials again.

________ *Read instruction #2& run experiment*

________ Pay/Debrief & Wrap-up

Instruction #1: This is an auditory perception experiment. You will hear two tones in sequence and have to decide if the second tone moves up or down from the first. If you think the second tone is higher than the first tone, press the up arrow. If you think the second tone is lower than the first tone, press the down arrow.

If you are unsure of your answer, then just respond with your first, spontaneous impression.

First, you are going to complete some practice trials. There are 24 trials and you will be given feedback if your choice is correct or incorrect. Please only respond after you hear both tones played. If the computer does not proceed to the next trial after your response, please let the experimenter know.

Do you have any questions?

You can start once I exit the sound booth.

Instruction #2: Now you are going to start the experiment. Again, you will hear two tones and have to decide whether the second tone is higher or lower than the first. Remember only to push the arrow after both tones play. Whenever you are not sure, please respond with your first and spontaneous impression. You will not receive feedback on your answers for the next part.

The experiment takes about 25 minutes, and there is a 5-minute break halfway through. Do you have any questions?

You can start once I exit the sound booth.

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VITA

Elizabeth Petitti graduated from Barnard College, Columbia University with a Bachelor of Arts in Linguistics and Psychology in 2013. During her undergraduate years, she worked with the Spoken Language Processing Group under Dr. Julia Hirschberg to examine cross-linguistic markers of deception in speech. In order to continue to pursue a love of research, she worked in the Child Language Laboratory under Dr. Sudha Arunachalam and the Communication Neuroscience Research Laboratory under Dr. Tyler Perrachione at Boston University. Elizabeth continues to enjoy bridging the gap between research and clinical practice, and will begin her Clinical Fellowship year upon completion of the Speech-Language Pathology Master of Science program in May of 2015. She can be reached by email at emp.slp@gmail.com